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by

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UNITED STATES
NAVAL POSTGRADUATE SCHOOL

THESIS

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ABSTRACT

This thesis describes a method by which near-surface temperature inversions in the ocean may be classified. Although categories of sub-thermocline ducts for sound transmission, formed as a result of these temperature inversions, have been studied in detail in the North Pacific Ocean, classifications are general enough to be applied to ducts in other regions.

A considerable variety of sub-thermocline ducting is present in the North Pacific. This variability shows both a seasonal and a positional dependence which may be explained on a stability basis utilizing data obtained from selected Nansen casts reported for stations throughout the North Pacific.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

CHAPTER I

INTRODUCTION

The typical vertical temperature distribution in the open ocean is usually one of decreasing temperature with increasing depth. Although this is the general case, it is by no means completely universal, and variations are prominent in certain regions of the world ocean. Ten near-surface thermal structure types have been classified by Laevastu and Stevens (1968). One of these is the sub-thermocline duct type, which can be found in large areas of the North Pacific, or in smaller areas of the North Atlantic Ocean.

To date few investigations into this particular feature have been made in any detail. An optimum region for the study of duct characteristics is the North Pacific Ocean because of the great variety of ducts which exist there, and because of the extremely large area of the North Pacific over which the duct can be found. Therefore research into the sub-thermocline duct for purposes of this thesis has been limited to the North Pacific Ocean.

Although limited in area of interest to the North Pacific Ocean, this thesis does describe the sub-thermocline duct with its seasonal and positional variations for that ocean in detail. To facilitate this purpose, duct types have been classified into five major categories, each of which is subdivided into smaller categories. Although classification is based on ducts observed in the North Pacific, these categories, defined here, should apply equally well to ducts found in other oceans.

CHAPTER II

DUCT NOMENCLATURE

The sub-thermocline duct is a feature of the temperature-depth profile found where a temperature inversion exists below the thermocline. This duct, when present, is generally found in the upper few hundred meters of the ocean, and is not to be confused with the deep sound channel which is a general feature of ocean sound transmission below regions possessing thermoclines.

Before an attempt is made to describe or classify a sub-thermocline duct, key features of the temperature profile, and of the duct itself, must be defined. These definitions are illustrated in Figure 1.

The mixed layer depth is the depth to which water is mixed through wave action or thermohaline convection. Below the mixed layer is the thermocline, which is that portion of the temperature-depth profile showing a marked negative temperature gradient that is greater than the gradients above or below it. The magnitude of the thermocline is the total temperature change encountered along the thermocline.

The first step in the treatment of the duct itself is to draw a vertical line from the point of maximum temperature in the inversion layer up to the point where it meets the thermocline. This line sets the vertical limits of the duct, and the length of this line is defined as the duct thickness. The top of the duct is defined by the point where the thickness

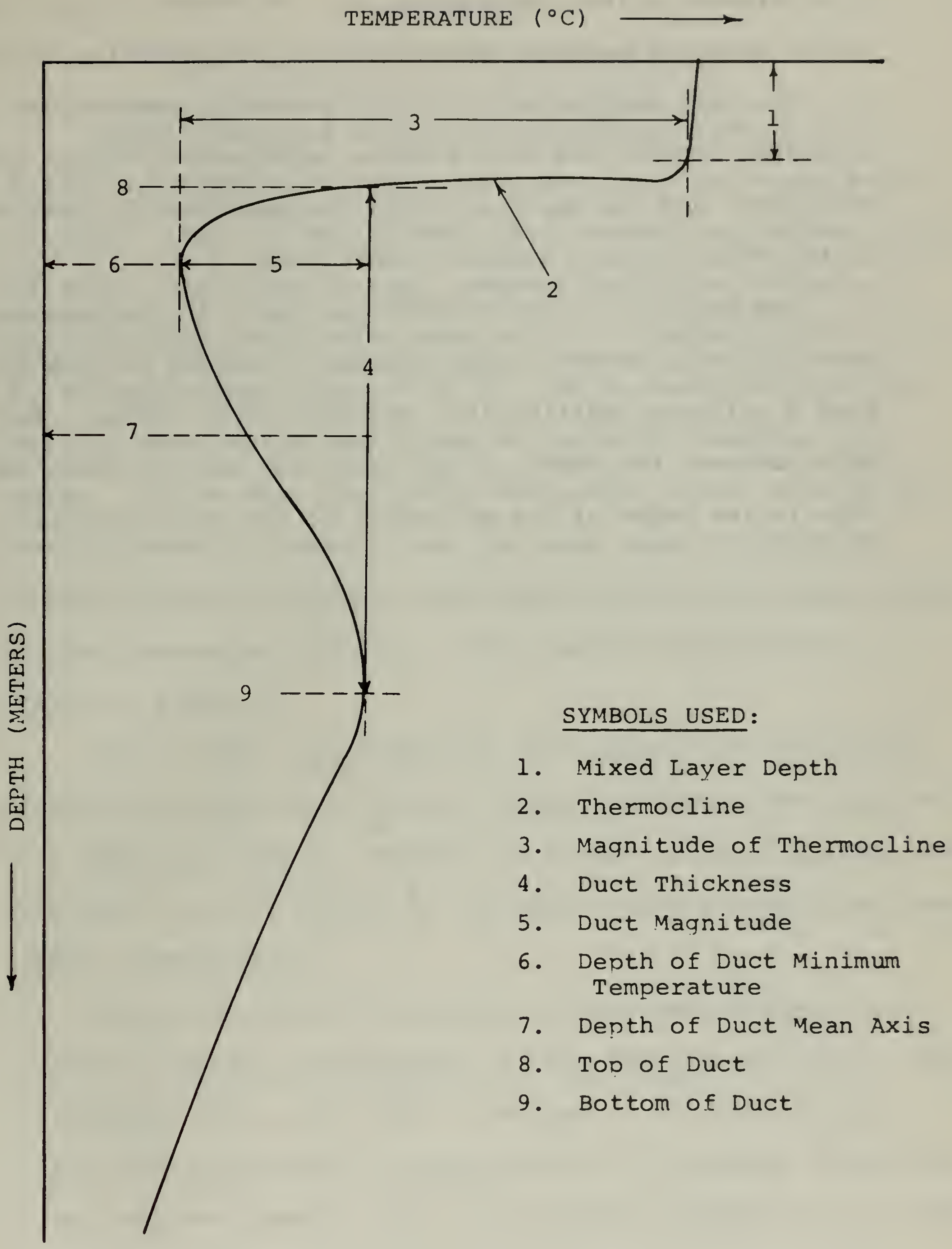

Figure 1

SUB-THERMOCLINE DUCT NOMENCLATURE

line intersects the thermocline, and the bottom of the duct is the point of maximum temperature in the inversion layer.

The duct magnitude is the difference in temperature encountered between the duct minimum temperature and the thickness line, and the depth at which the magnitude is measured is the depth of duct minimum temperature.

The majority of sub-thermocline ducts are not symmetric about an axis; however, some feature is needed to give the duct a relative position in a vertical water column. For this purpose, the depth of the duct mean axis is used, and this is the depth of the mid-point of the thickness line.

CHAPTER III

SUB-THERMOCLINE DUCT CLASSIFICATION

In this detailed investigation of the North Pacific Ocean, sub-thermocline ducts were generally not found south of 35 N. Into the Bering Sea, data becomes very sparse north of 60 N. With this in mind, extreme limits on the area of most detailed examination were set at a southern limit of 30 N, and a northern limit of 60 N. The eastern limits on the area of observation were fixed at the North American west coast. To the west the limits went along 140 E, then up the eastern coast of Honshu, past the east coast of Hokkaido, along the Kurile Islands, and finally along the eastern coast of the Kamchatka Peninsula. The area of investigation is shown in Figure 2.

Tully (1964) set limits on four regions of water mass formation in the North Pacific Ocean. Of these four regions, the Subarctic Region, as shown in Figure 3, is of primary importance, as this region is included entirely within the area under investigation.

Data were obtained primarily from Nansen casts as reported in <u>Oceanic Observations of the Pacific</u> (Pre-1949, 1949, 1955 NORPAC Data, and 1959). Because of the type of data used, duct measurements depend heavily on personal interpretation, and measurements can vary slightly depending on how temperature profiles are constructed between sampling depths. At many stations a duct was obviously present, but vertical spacing of 100 to 150 meters between Nansen bottles made even reasonably accurate estimates of duct measurements impossible

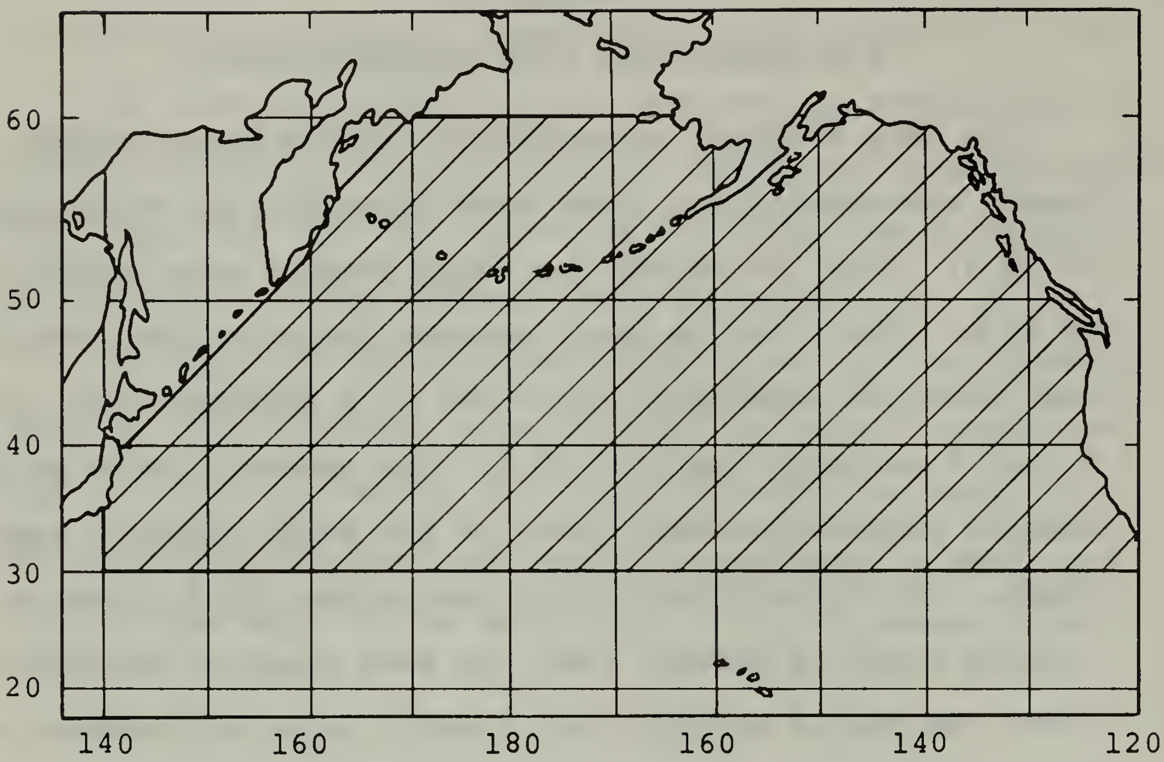

Figure 2. AREA OF NORTH PACIFIC UNDER INVESTIGATION

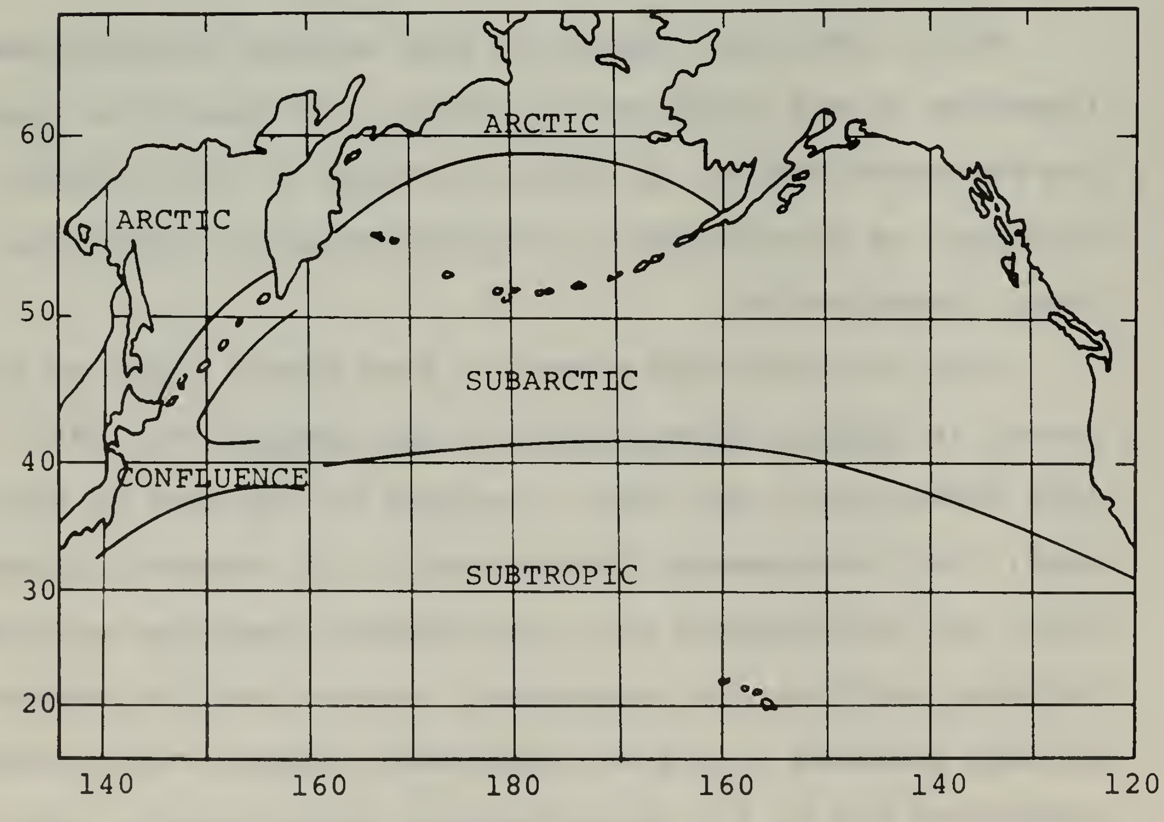

Figure 3
SUBARCTIC REGION ADAPTED FROM TULLY (1964)

for these stations. The number of stations considered reached well into the thousands; however, useful data could be collected at only approximately 750 of these stations.

Ideally, data for this type of study should be taken at fixed locations throughout the area of investigation for all seasons of the year. A major problem resulted from the fact that data were obtained only from specific cruises. This gave a large concentration of data in certain areas and seasons, and a marked lack of data in other areas and times.

Because of the very rough sea conditions throughout the area of investigation during the winter months, data were scarce from mid-September to late April, and the bulk of the winter data was taken from a single report on the Boreas Expedition (1966).

Classification of ducts and their trends depend heavily on some 366 ducts which were actually drawn and carefully measured. These ducts ranged across the Subarctic Region; however, measurements in the south-central portion of the region were quite sparse. A heavy concentration of data taken in 1955 (the NORPAC data) was used in order to get a good indication of duct trends for the entire region of the Subarctic over a relatively short time span. The NORPAC data comprised 59.6 percent of those ducts drawn. Data from other years confirmed conditions found in 1955 and 1966. The number of ducts actually drawn, by years, are presented in Table I, and the number of ducts drawn, by months, are presented in Table II.

TABLE I

NUMBERS AND PERCENTAGES OF DUCTS DRAWN BY YEARS

YEAR	NUMBER OF DUCTS	PERCENTAGE OF TOTAL
1934	5	1.4
1947	9	2.5
1949	62	17.0
1955	219	59.6
1959	15	4.1
1966	56	15.4

TABLE II

NUMBERS AND PERCENTAGES OF DUCTS DRAWN BY MONTHS

MONTH	NUMBER OF DUCTS	PERCENTAGE OF TOTAL
JAN	7	2.0
FEB	44	12.0
MAR	9	2.5
APR	5	1.4
MAY	10	2.7
JUN	10	2.7
JUL	69	18.9
AUG	164	44.6
SEP	36	9.9
OCT	4	1.1
NOV	8	2.2
DEC	0	0.0

In the classification of ducts, three measurements are of primary importance. These are the duct magnitude, duct thickness, and depth of duct mean axis. A fourth measurement which was considered in detail because of its importance in sound studies in the ocean was the depth of duct minimum temperature. This fourth measurement was necessary due to the fact that very few ducts are symmetrical about their mean axis.

Because of the major dependence of sound speed on temperature, the three common forms of single sub-thermocline ducts have been classified on the basis of duct magnitude. To complete the five major categories of ducts, two supporting categories have been classified by other means.

Category A ducts (small ducts) are all single ducts below the thermocline with a magnitude of less than 1.00 C. In data collection those ducts of magnitude less than 0.10 C normally were not considered.

Category B ducts (moderate ducts) are all single ducts below the thermocline whose magnitude is between 1.00 and 1.99 C.

Category C ducts (large ducts) are all single ducts below the thermocline with a magnitude of 2.00 C or greater.

Category D ducts are multiple ducts below the thermocline, and for this major category, no limitation is placed on the magnitudes of the ducts. Invariably ducts falling into this category consisted of two separate ducts. Many large single ducts which were actually drawn did appear to be in the process of being split into two smaller ducts; however,

as long as the intermediate temperature inversion splitting the duct did not reach the temperature at the thickness line these ducts were not considered as Category D ducts.

Although surface ducts do not fit the definition of a sub-thermocline duct as such, they are quite predominant throughout the region under investigation during winter months, and they play an important role in the actual formation of the sub-thermocline ducts in the Subarctic Region. For these reasons, Category E, which is a supporting category, is that of the surface duct. Category E ducts may have small ducts below the major surface duct.

The five major duct categories are summarized in Table III, and a breakdown of the 366 ducts drawn is presented in Table IV. Common examples of each major category of duct are shown in Figures 4, 5, 6, 7, and 8.

Once a single sub-thermocline duct has been placed into one of its three major categories, further classification is desirable, primarily to give the duct a relative position in a vertical water column. This is necessary because of the large range of values through which the duct thickness and the depth of duct mean axis can vary for category A, B, and C ducts. Category D ducts are best sub-classified on the basis of duct magnitudes and the vertical separation between ducts, and category E ducts on the basis of duct magnitude and duct thickness. All duct sub-categories are defined in Table V.

TABLE III

DUCT MAJOR CATEGORIES

CATEGORY	DUCT TYPE	MAGNITUDE
A	Small duct below the thermocline	Less than 1.00 C
B	Moderate duct below the thermocline	1.00 to 1.99 C
C	Large duct below the thermocline	2.00 C and greater
D	Multiple ducts below the thermocline	------------------
E	Surfact duct	------------------

TABLE IV

NUMBERS AND PERCENTAGES OF DUCTS DRAWN BY MAJOR CATEGORIES

CATEGORY	NUMBER OF DUCTS	PERCENTAGE OF TOTAL
A	191	52.0
B	52	14.3
C	28	7.7
D	35	9.6
E	60	16.4

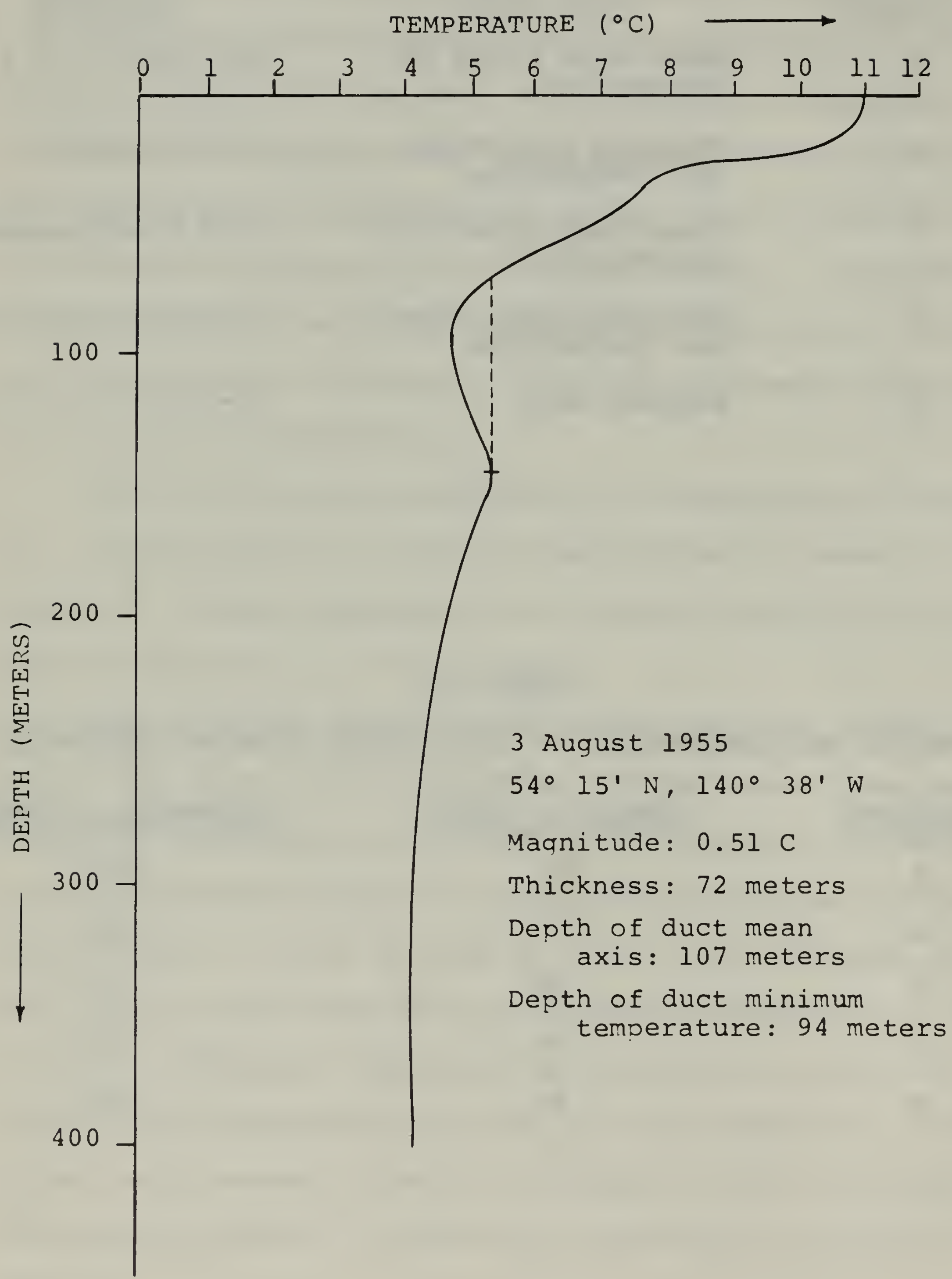

Figure 4

TYPICAL CATEGORY A DUCT

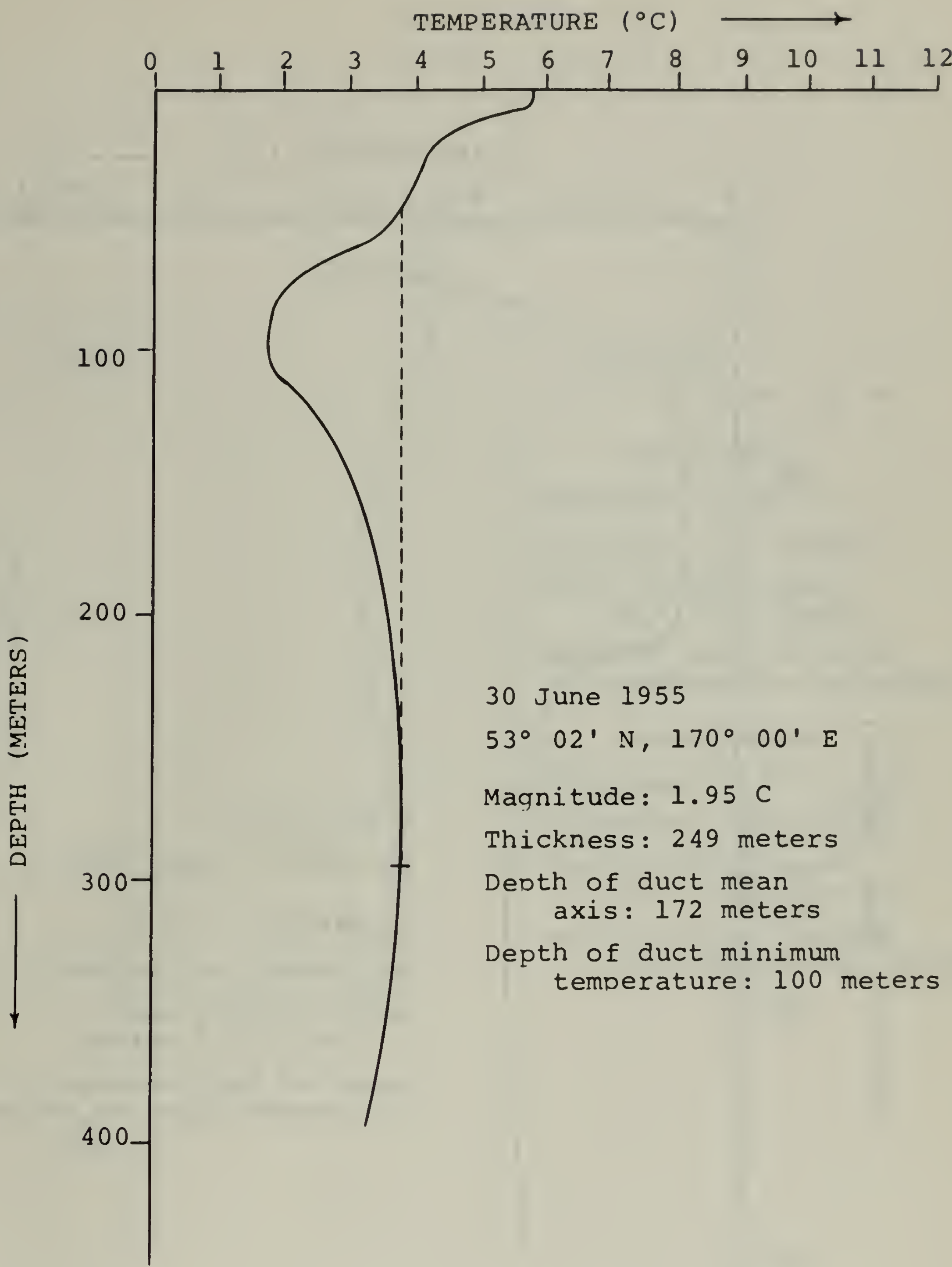

Figure 5

TYPICAL CATEGORY B DUCT

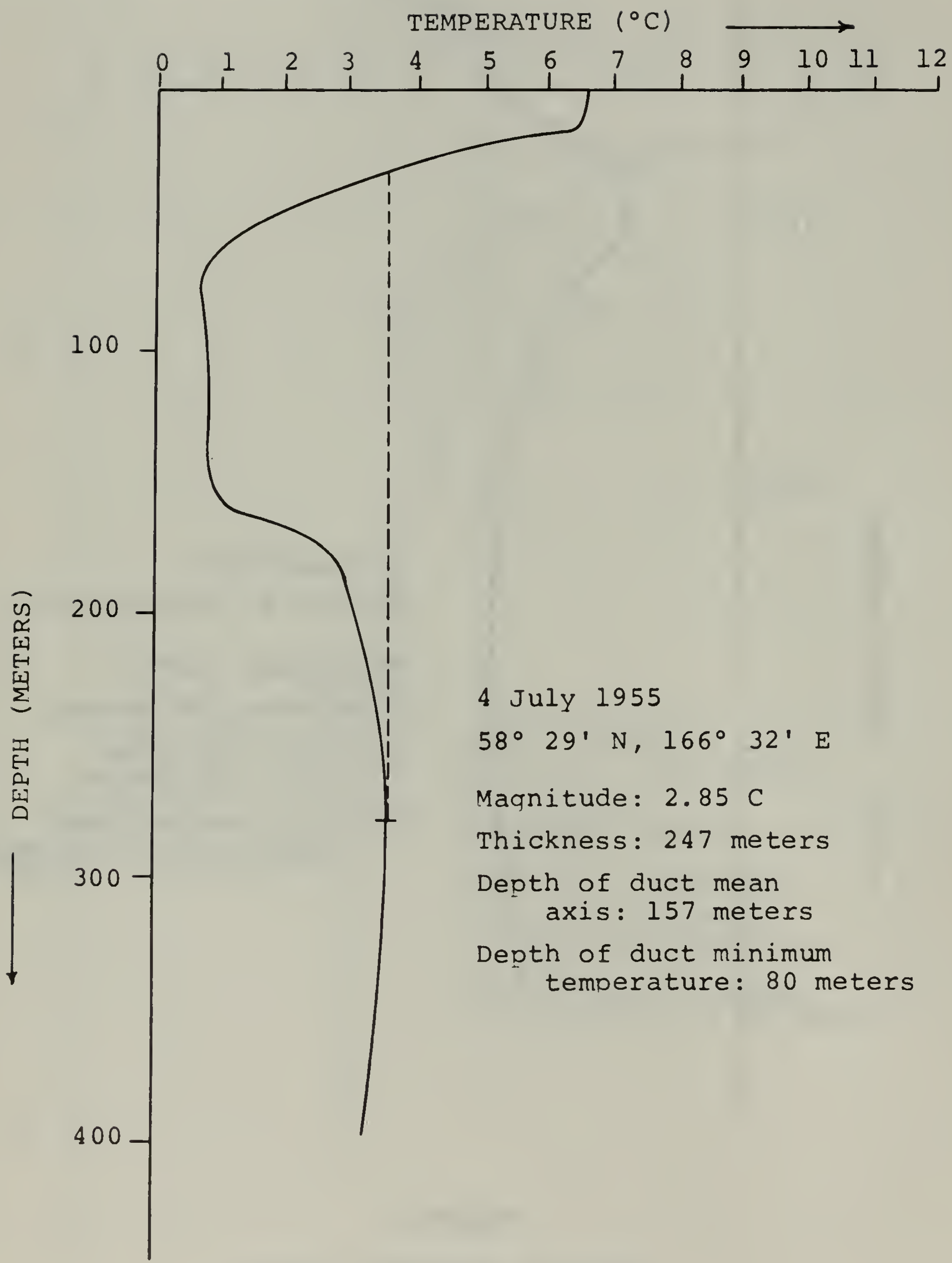

Figure 6

TYPICAL CATEGORY C DUCT

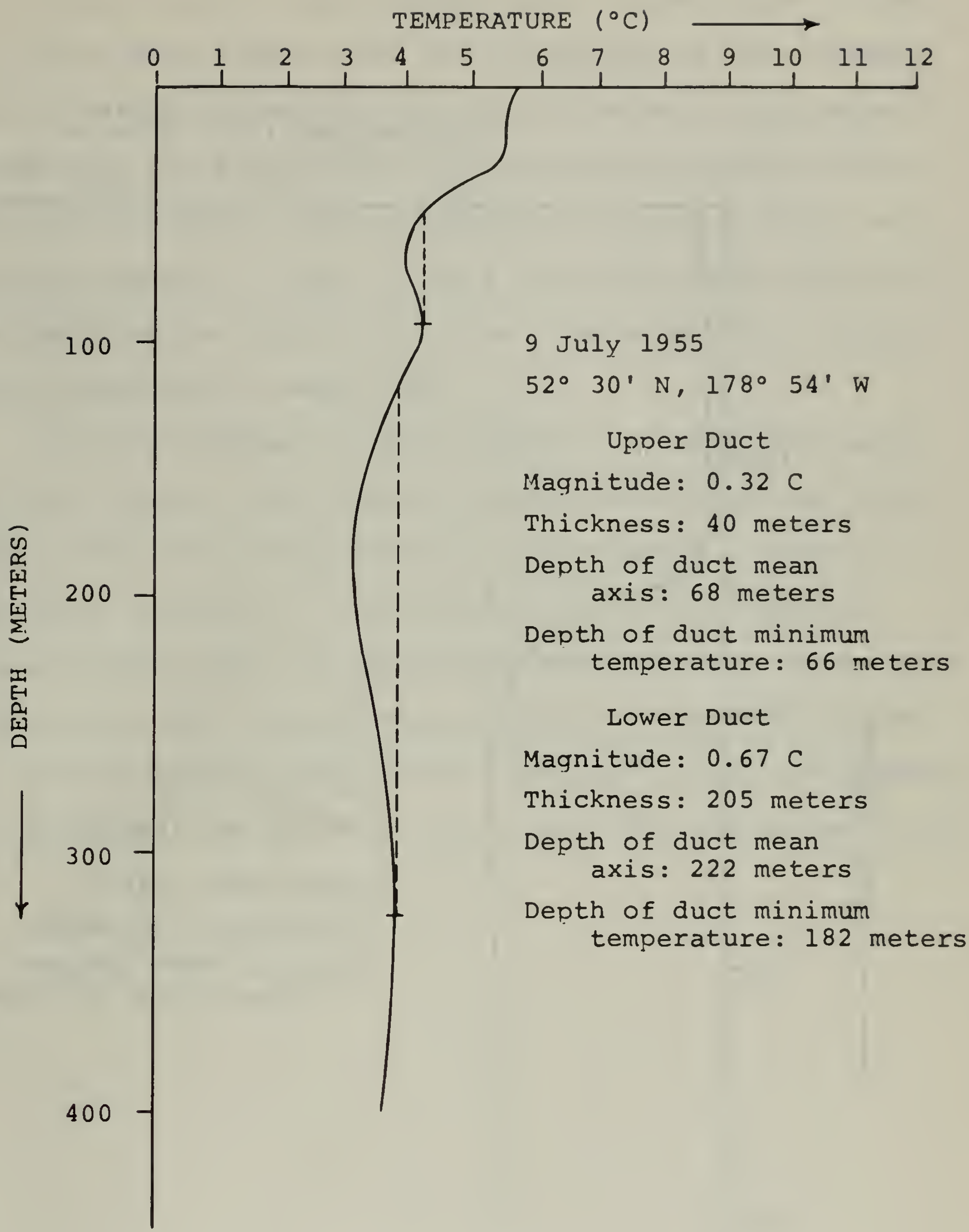

Figure 7

TYPICAL CATEGORY D DUCT

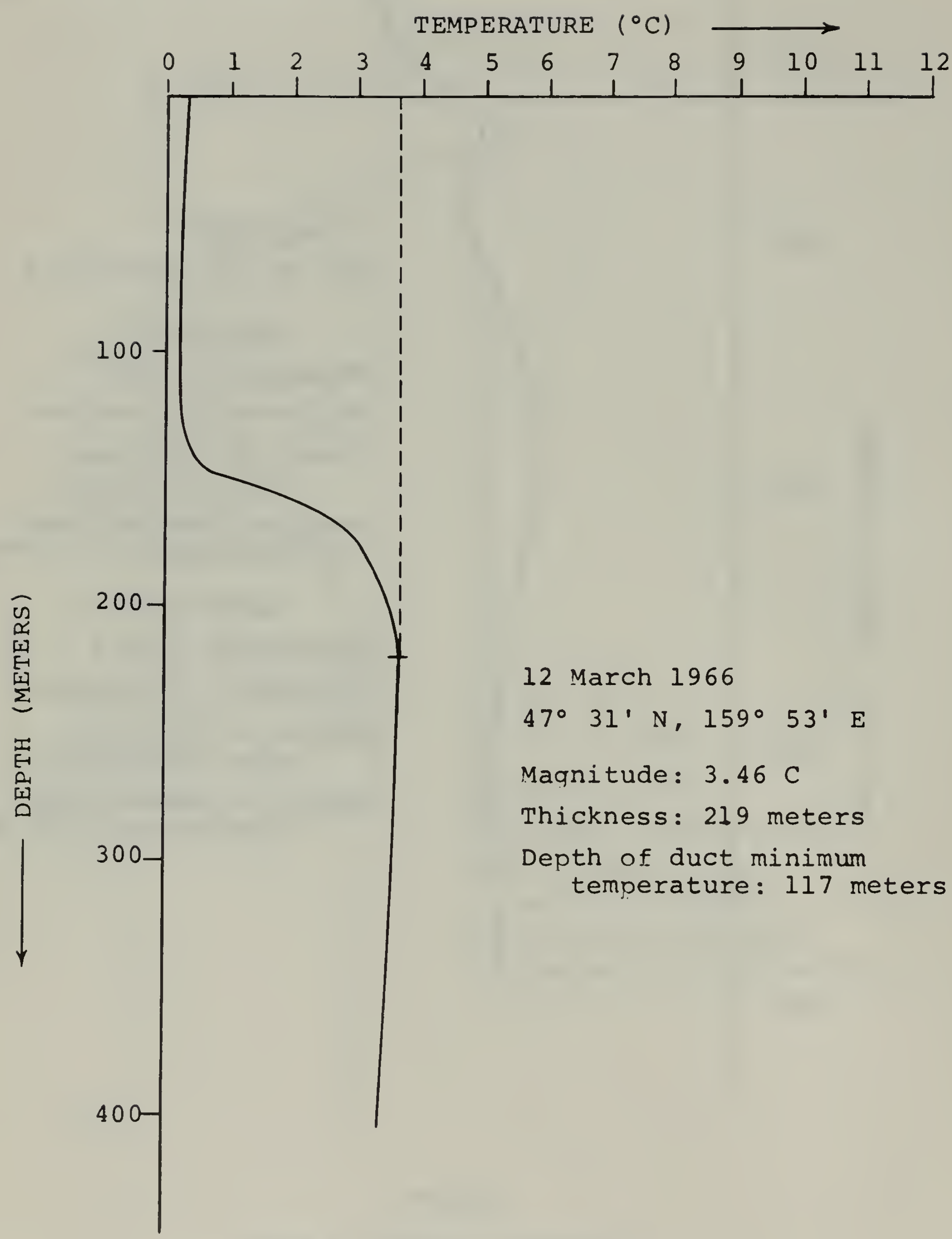

Figure 8

TYPICAL CATEGORY E DUCT

Table V gives a sub-category with a combination letter and number designation. The letter portion of this designation is retained from the duct major category. The number pertains to the appropriate description of the duct within that major category. Major category A, B, and C ducts are grouped together in Table V since the descriptive portion of the table applies equally to ducts in each of these categories, regardless of magnitude.

It is of interest in duct analysis to break down each duct sub-category into numbers and percentages of the total ducts within their respective major categories. This has been done in Table VI, but because of the type sampling, these figures cannot be considered representative of the entire region under consideration. This is particularly true of category E ducts where, of the number of ducts considered but not drawn, the majority easily fell into sub-category E-7.

TABLE V

DUCT SUB-CATEGORIES

SUB-CATEGORY	DESCRIPTION
A-1 B-1 C-1	Thickness less than 100 meters Duct mean axis above 200 meters
A-2 B-2 C-2	Thickness less than 100 meters Duct mean axis 200 meters and below
A-3 B-3 C-3	Thickness between 100 and 250 meters Duct mean axis above 200 meters
A-4 B-4 C-4	Thickness between 100 and 250 meters Duct mean axis 200 meters and below
A-5 B-5 C-5	Thickness between 250 and 400 meters (No limitation on duct mean axis)
A-6 B-6 C-6	Thickness greater than 400 meters (no limitation on duct mean axis)
D-1	Both ducts of magnitude less than 0.50 C Vertical separation between bottom of higher duct and top of lower duct less than 100 meters
D-2	Both ducts of magnitude less than 0.50 C Vertical separation between bottom of higher duct and top of lower duct of 100 meters or greater
D-3	Higher duct of magnitude 0.50 C or greater Lower duct of magnitude less than 0.50 C (No limit on vertical separation
D-4	Higher duct of magnitude less than 0.50 C Lower duct of magnitude 0.50 C or greater (No limit on vertical separation)

TABLE V (Continued)

SUB-CATEGORY	DESCRIPTION
D-5	Both ducts of magnitude 0.50 C or greater (No limit on vertical separation)
E-1	Surface duct of any magnitude with one or more smaller ducts below it
E-2	Magnitude less than 1.00 C Thickness less than 200 meters
E-3	Magnitude less than 1.00 C Thickness 200 meters or greater
E-4	Magnitude of 1.00 to 2.00 C Thickness less than 200 meters
E-5	Magnitude of 1.00 to 2.00 C Thickness of 200 meters or greater
E-6	Magnitude greater than 2.00 C Thickness less than 200 meters
E-7	Magnitude greater than 2.00 C Thickness of 200 meters or greater

TABLE VI

NUMBERS AND PERCENTAGES OF DUCTS DRAWN BY SUB-CATEGORIES

SUB-CATEGORY	NUMBER OF DUCTS	PERCENTAGE OF TOTAL
	CATEGORY A: 191 DUCTS	
A-1	138	72.2
A-2	1	0.5
A-3	17	8.9
A-4	19	10.0
A-5	11	5.8
A-6	5	2.6
	CATEGORY B: 52 DUCTS	
B-1	5	9.6
B-2	1	1.9
B-3	13	25.0
B-4	1	1.9
B-5	10	19.2
B-6	22	42.4
	CATEGORY C: 28 DUCTS	
C-1	0	0.0
C-2	0	0.0
C-3	12	42.8
C-4	1	3.6
C-5	8	28.6
C-6	7	25.0

TABLE VI (Continued)

SUB-CATEGORY	NUMBER OF DUCTS	PERCENTAGE OF TOTAL
	CATEGORY D: 35 DUCTS	
D-1	17	48.6
D-2	5	14.3
D-3	7	20.0
D-4	4	11.4
D-5	2	5.7
	CATEGORY E: 60 DUCTS	
E-1	4	6.7
E-2	22	36.7
E-3	7	11.7
E-4	12	20.0
E-5	5	8.3
E-6	2	3.3
E-7	8	13.3

CHAPTER IV

SEASONAL VARIATIONS OF THE SUB-THERMOCLINE DUCT IN THE NORTH PACIFIC

Ducts in the North Pacific Ocean show a definite seasonal cycle, as well as variation with location. Dodimead, Favorite, and Hirano (1962) have defined heating and cooling cycles of temperature structures at Ocean Station "P" which, when applied to the entire Subarctic Pacific, have proven useful in the description of duct variations.

Ducts have been grouped according to heating and cooling periods, considering the average heating period of the Subarctic Region as consisting of the months of April through September, and the average cooling period as October through March. The area of concentrated data collection (previously shown in Figure 2) was subdivided into five sectors as shown in Figure 9.

Primary ducts considered as a basis for trend analysis consisted of the 366 ducts which were drawn as well as 96 category E ducts which were not drawn. These ducts were separated by heating and cooling periods and then by sectors. The number of ducts falling into each sector during the heating period are shown in Table VII, and those in each sector during the cooling period in Table VIII.

Uda (1963) has defined three zones in the salinity structure of the Subarctic Region. These are an upper zone, a transition zone, and a lower zone. It is the transition

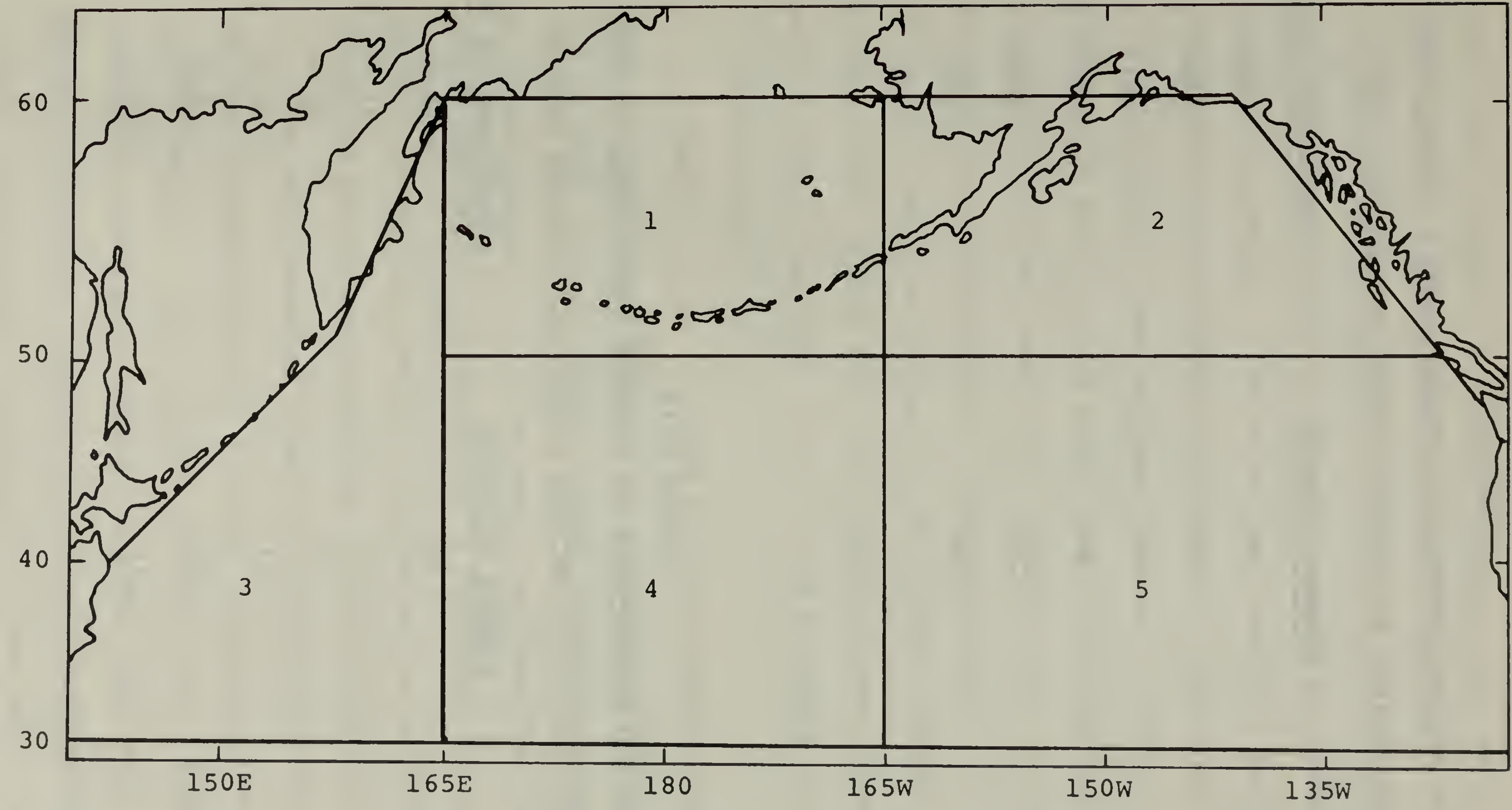

Figure 9

SUBDIVISIONS OF NORTH PACIFIC REGION UNDER INVESTIGATION

TABLE VII

NUMBERS AND PERCENTAGES OF PRIMARY DUCTS FOUND IN THE NORTH PACIFIC BY SECTORS DURING THE HEATING PERIOD

SECTOR	NUMBER OF DUCTS	PERCENTAGE OF TOTAL
1	68	23.5
2	62	21.4
3	72	24.8
4	27	9.3
5	61	21.0
TOTAL	290	100.0

TABLE VIII

NUMBERS AND PERCENTAGES OF PRIMARY DUCTS FOUND IN THE NORTH PACIFIC BY SECTORS DURING THE COOLING PERIOD

SECTOR	NUMBER OF DUCTS	PERCENTAGE OF TOTAL
1	44	25.5
2	25	14.5
3	55	32.0
4	34	19.8
5	14	8.2
TOTAL	172	100.0

zone, where the main halocline exists, that is of primary importance in sub-thermocline duct formation.

In the eastern portion of the Subarctic Region a permanent halocline exists at a depth generally somewhere between 100 and 200 meters. The halocline generally becomes less pronounced when crossing the Subarctic from east to west.

Winter data were extremely sparse in sector 5, and in the eastern half of the sector data obtained for the cooling period were either very early or very late in the period. In this part of the sector ducts of category A-1 were found primarily, with an indication of surface cooling forming small surface ducts along the North American west coast. Cooling period data in sectors 1, 2, 3, and 4 showed a predominance of surface ducts.

Figures 10, 11, 12, and 13 show representative temperature and salinity profiles for both the heating and the cooling periods at four widely spread locations across the area of investigation. In each case a surface duct was present during the cooling period, and a sub-thermocline duct existed during the heating period, indicating the marked seasonal variation of duct characteristics found throughout this region.

The same seasonal trend of sub-thermocline duct formation and decay appeared to be followed throughout the region of investigation. With a mature surface duct, generally a near-isothermal condition existed to some depth very near the top of the halocline. Normally in this situation temperature increased through the halocline, and then began decreasing with

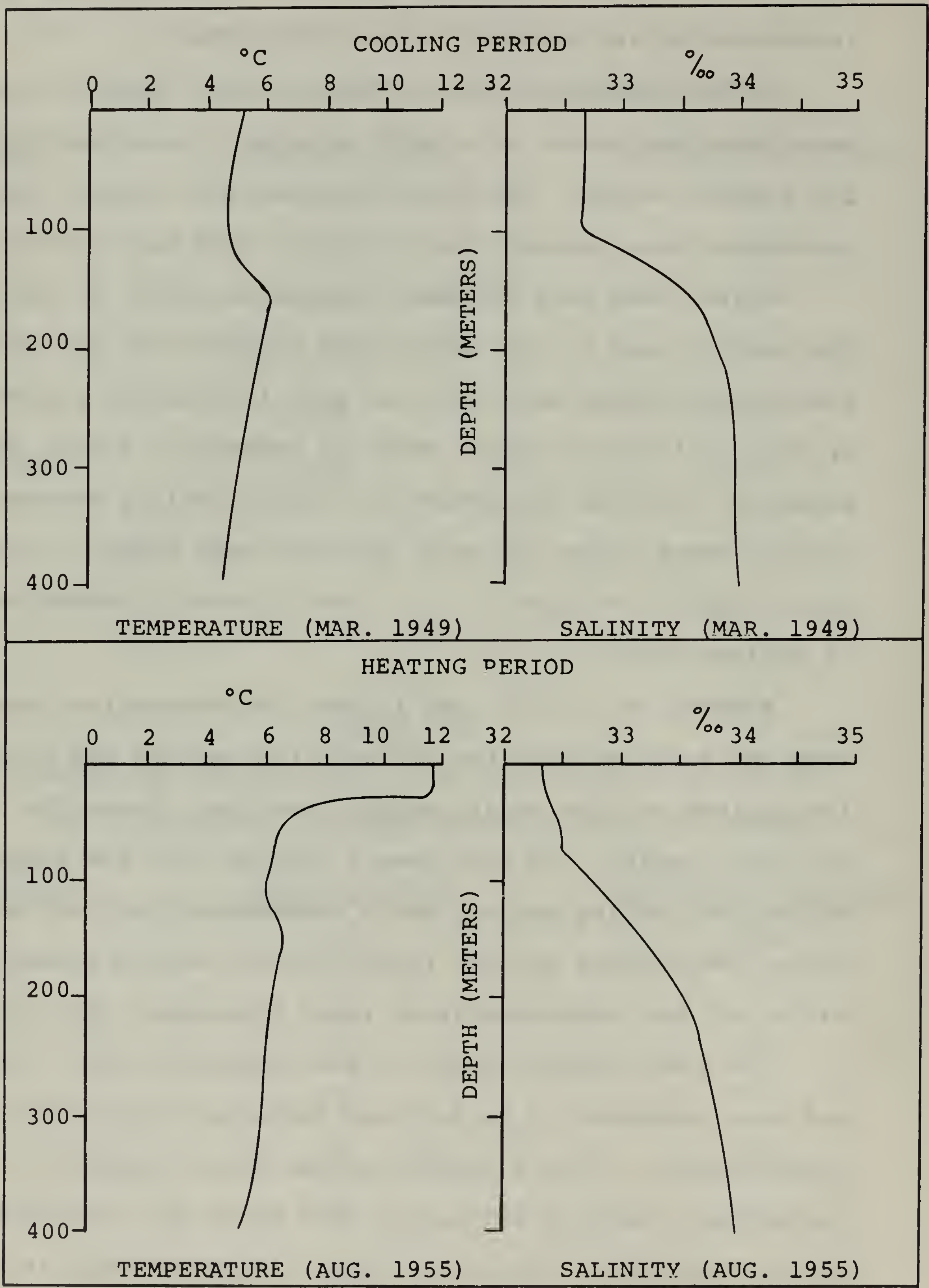

Figure 10

TYPICAL TEMPERATURE AND SALINITY PROFILES FOR HEATING AND COOLING PERIODS AT 52 N, 137 W

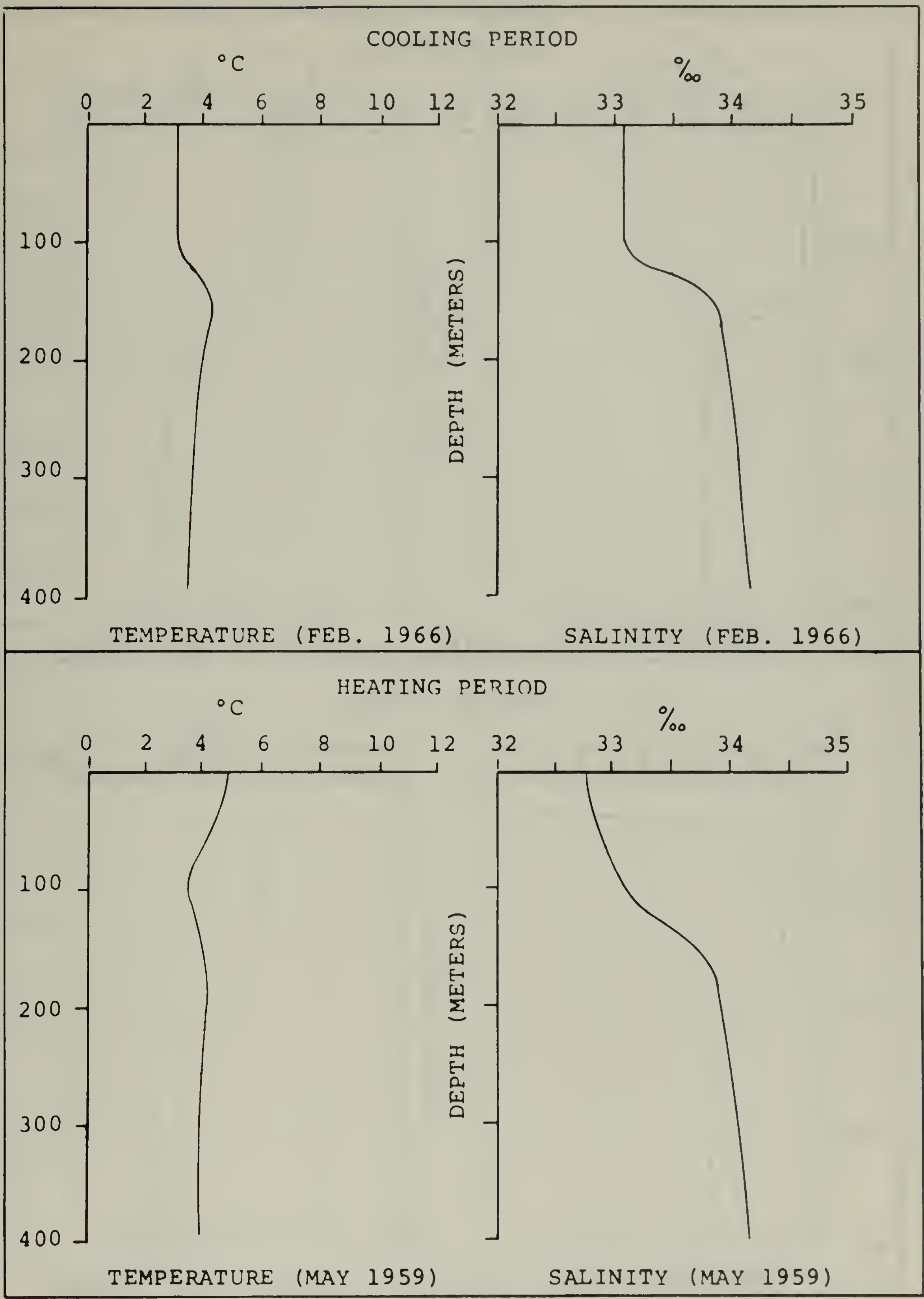

Figure 11

TYPICAL TEMPERATURE AND SALINITY PROFILES FOR HEATING AND COOLING PERIODS AT 52 N, 175 E

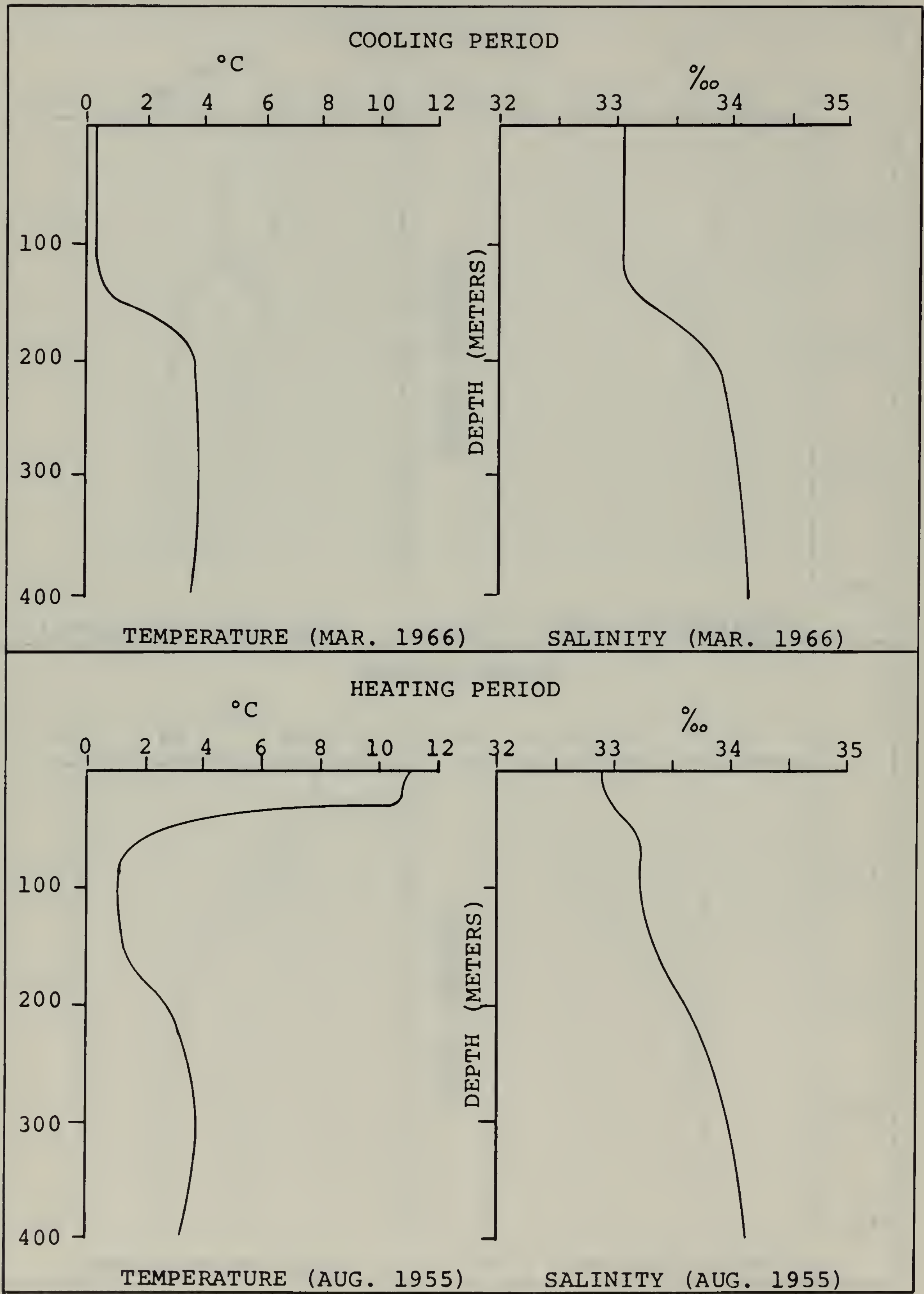

Figure 12

TYPICAL TEMPERATURE AND SALINITY PROFILES FOR HEATING AND COOLING PERIODS AT 47 N, 160 E

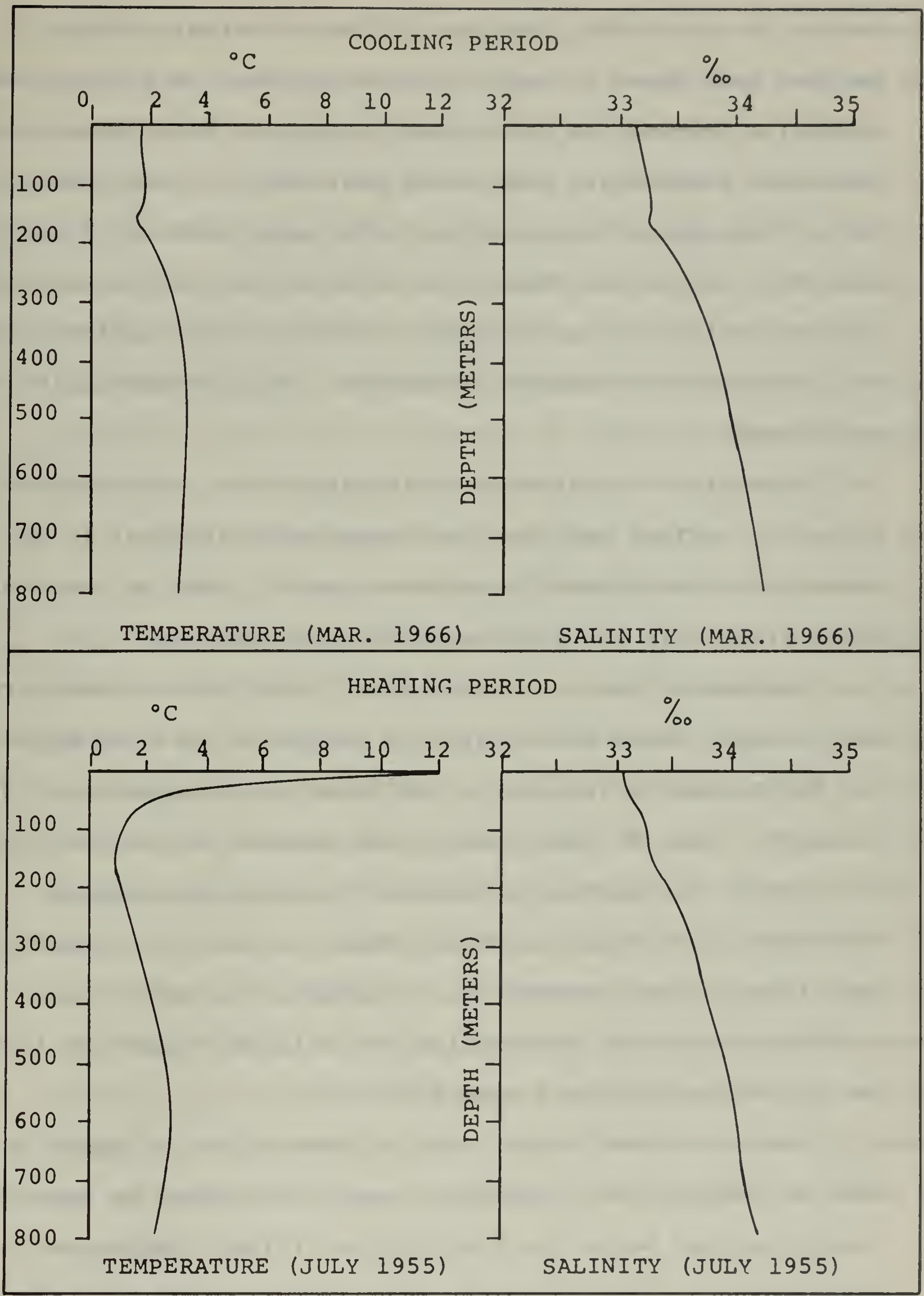

Figure 13

TYPICAL TEMPERATURE AND SALINITY PROFILES FOR HEATING AND COOLING PERIODS AT 43 N, 146 E

depth. In the Spring the top of the isothermal portion of the surface duct began to warm from the surface. With continued heating a thermocline was formed, and as surface temperatures increased the surface duct would give way to a sub-thermocline duct. Throughout this evolution the lower portion of the surface duct, being too deep to be affected by surface processes, remained relatively unchanged. Therefore with surface heating and pronounced thermocline formation, the sub-thermocline duct was formed.

Reversing this process in the late Fall, with advanced stages of surface cooling, the temperature gradient in the thermocline was gradually decreased until, late in the cooling period, only the surface duct again remained.

Dodimead, Favorite, and Hirano (1962) have stated certain general rules of temperature structure behavior which can be applied to regions not affected by convergence or divergence. Two of these rules, when applied to the sub-thermocline duct, may partially explain the ducts persistence throughout the heating period. First, no heat is transferred down through the thermocline. Secondly, the temperature structure below the thermocline can only be changed by internal processes which are generally slow.

Based on these rules, once a thermocline is formed by surface heating over a surface duct, few changes to temperature structure below the thermocline will be experienced, and these changes, when existing, will probably take long periods of time. The halocline in the North Pacific Ocean generally

begins anywhere from 100 meters to 250 meters which is too great a depth for the thermocline to reach, but not too deep for surface cooling to reach when no thermocline exists. Temperatures in the halocline generally increase with depth, both for the heating and the cooling periods. It is the halocline, therefore, that tends to be the lower limit of isothermal conditions in the cooling period; however, duct thicknesses indicate ducts larger than the isothermal layer because of the generally slow rate of increase of temperature in the halocline to some maximum near the bottom of the halocline.

Based on these observations, the surface waters in the cooling period cause isothermal conditions to extend to the halocline, where temperature begins to increase with depth. Near the bottom of the halocline a maximum temperature is reached which varies little throughout the year. This maximum temperature forms the bottom of the duct. With surface heating the thermocline grows until, at some time when the surface temperature exceeds the temperature at the bottom of the duct, the sub-thermocline duct appears. The bottom of the duct remains unchanged until the next winter, while the top of the duct changes with the magnitude of the thermocline and the mixed layer depth. This process indicates that the sub-thermocline duct could be used as a good indication of the severity of the previous winter conditions, as signified by Tully and Giovando (1963).

CHAPTER V

POSITIONAL VARIATIONS OF THE SUB-THERMOCLINE DUCT IN THE NORTH PACIFIC

Although ducts in the North Pacific Ocean occur primarily within the area previously shown in Figure 2, this area served only to define rough guidelines to follow in data collection. Ducts were not found throughout the entire region, so for further clarification an area of probable ducting was constructed.

Construction of the area of probable sub-thermocline ducting was hampered by the thinly distributed data in the south-central portion of the Subarctic Region, primarily in sector 4. Because of the scarcity of data along the southern portion of this sector, those ducts which were previously drawn had to be supplemented by additional data obtained from selected Nansen casts in Oceanic Observations of the Pacific for the years 1953, 1954, 1957, and by vertical temperature sections along selected longitudes for short time periods in 1961, 1962, 1963, and 1964 which were obtained from the Fleet Numerical Weather Central, at Monterey, California.

The southern limit of probable ducting still had to be interpolated in some instances; however, ducting seemed to follow closely the southern boundary of the Subarctic Region in sectors 4 and 5. This was heavily weighted whenever interpolation was required by a marked lack of data in these sectors. Combining these data led to the area of probable sub-thermocline ducting shown in Figure 14.

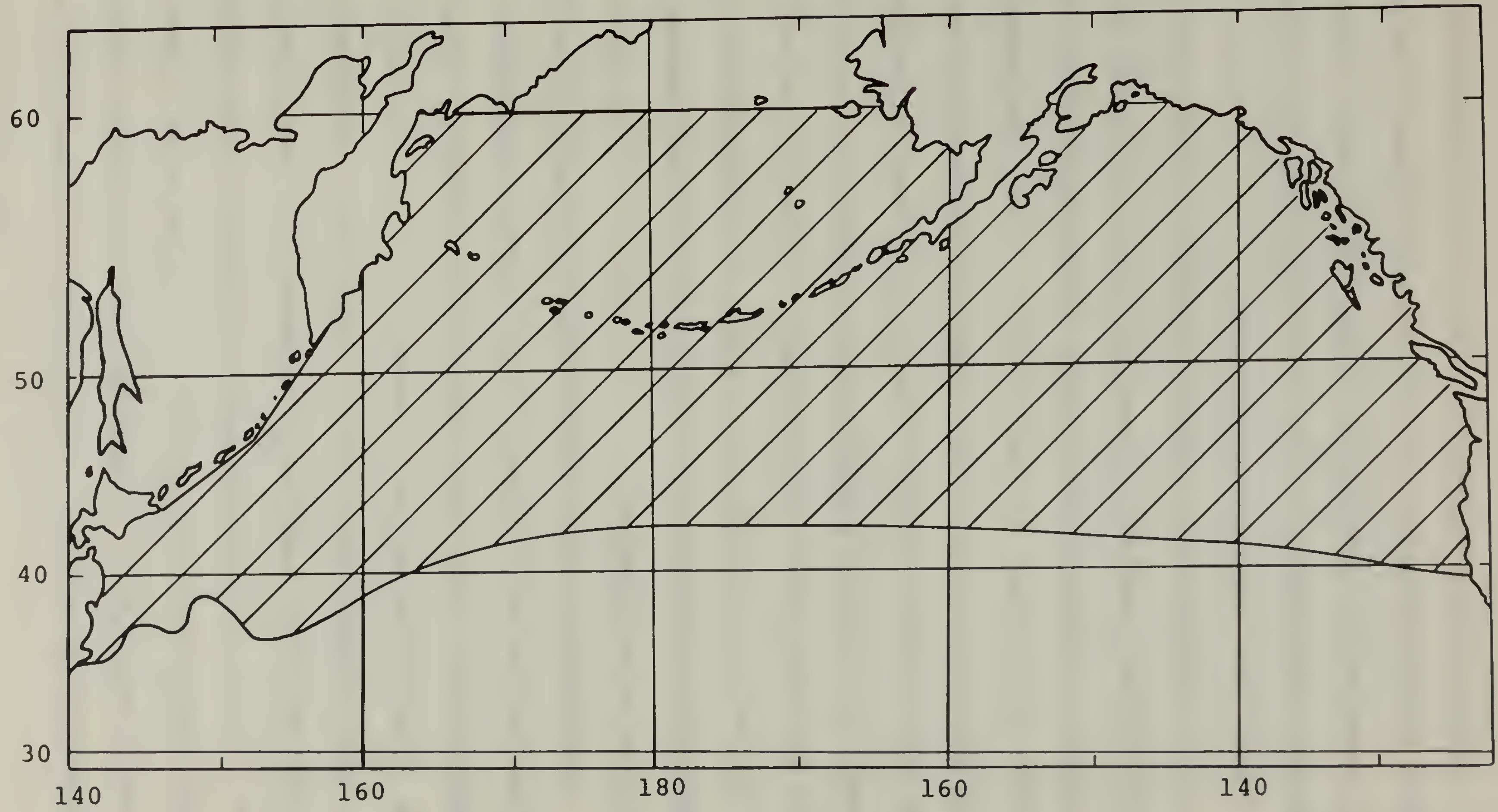

Figure 14

AREA OF PROBABLE SUB-THERMOCLINE DUCTING IN THE NORTH PACIFIC

The southern limit of the area of probable ducting is not a fixed boundary, but rather an average "floating" boundary required by the yearly variation of ducts. This southern boundary was seen to shift up to two degrees latitude north or south from one year to the next.

In sector 3 the southern boundary of the area of probable ducting displayed irregularities attributed to the Kuroshio. Nagata (1968) stated that temperature inversions seldom occur south of the Kuroshio. This was definitely the case with data used in this study, and consequently the southern edge of the region of probable ducting in sector 3 follows closely the northern edge of the Kuroshio.

Although the northern edge of sector 1 was arbitrarily set at 60 N, duct size and density of distribution in that area indicated that ducts could be expected further north, into the Arctic Region.

Indications were that ducting also existed to the west of the Kurile Island chain into the Sea of Okhotsk. Data available for this region were far too sparse to get more than just an indication, however.

The overall boundaries of the region of probably ducting are not meant to indicate the presence of ducts at all locations within these boundaries. To the contrary, many stations within the given area showed no indication of a duct being present, especially in sectors 2 and 5; however, ducts were present within thirty to forty miles of these stations.

In order to study duct variations with location, the heating and cooling periods must again be utilized. The study conducted on this topic was concentrated on variations during the heating period because it was primarily during this period that the vast majority of cases fulfilling the definition of a sub-thermocline duct were found. Before treatment of the actual sub-thermocline duct variations, however, basic trends of the cooling period surface ducts must be introduced.

Cooling period data were far too sparse in sector 5 to determine accurate duct trends. The four conditions observed in the area still should be mentioned. First was the existence of sub-category A-1 ducts in the southeast portion of the area of probable ducting. Further into the heart of sector 5 normal profiles of temperature decreasing with depth were observed. To the north, near the boundary between sectors 2 and 5, two additional situations were observed, primarily from spot checking data without actually drawing the ducts. In one situation temperatures were nearly isothermal to a depth of 50 to 125 meters, whereupon they began decreasing with depth. The final situation encountered was that of routine surface ducts of small magnitude extending down to a depth between 50 and 125 meters.

Duct trends for the cooling period in sectors 1, 2, 3, and 4 were more easily recognizable. In sector 2 ducts were primarily in sub-categories E-2, E-4, and E-6, all of which have thicknesses less than 200 meters.

Following a counterclockwise rotation as a means of handling duct trend analysis, the next sector encountered would be sector 1. Here cooling period ducts were mainly grouped in sub-categories E-3, E-4, and E-5 in the southern half of the sector; however, further to the northwest in the same sector, sub-category E-5 ducts along with larger, deeper ducts in sub-category E-7 were prominent.

Further to the west, into sector 3, these E-7 ducts remained prominent. The E-7 ducts were also particularly prominent along the Kurile Island chain all the way south to an area off the east coast of Hokkaido. Further south subcategory E-1 and E-5 ducts appeared near the Kuroshio northern edge.

In sector 4 sub-category E-2 ducts were most readily found from about 45 N down to the southern boundary of the region of probable ducting. Data were extremely sparse for the northeast corner of this sector; however, in the northwest corner ducts were primarily in E-4 and E-5 subcategories.

During the heating period, a large variety of subthermocline duct sizes and shapes were observed throughout the region under investigation. The 290 primary heating period ducts considered in trend analysis have been broken down by sub-categories and sectors, and are summarized in Table IX. Category E ducts have not been included in this table for the simple reason that none were observed during the heating period.

TABLE IX

NUMBERS OF PRIMARY SUB-THERMOCLINE DUCTS IN EACH SUB-CATEGORY FOUND DURING THE HEATING PERIOD IN EACH SECTOR OF THE NORTH PACIFIC

SUB-CATEGORY	SECTOR 1	2	3	4	5
A-1	9	51	2	11	54
A-2	-	-	1	-	-
A-3	15	1	-	-	-
A-4	1	-	13	4	-
A-5	5	-	2	3	-
A-6	-	-	4	1	-
B-1	1	-	-	-	3
B-2	-	-	1	-	-
B-3	12	-	-	-	-
B-4	-	-	1	-	-
B-5	5	-	4	1	-
B-6	-	-	20	2	-
C-1	-	-	-	-	-
C-2	-	-	-	-	-
C-3	9	-	3	-	-
C-4	-	-	1	-	-
C-5	5	-	3	-	-
C-6	-	-	7	-	-
D-1	2	9	2	1	3
D-2	1	-	3	1	-
D-3	1	1	2	3	-
D-4	2	-	1	-	1
D-5	-	-	2	-	-

Category A, B, and C ducts appeared to be restricted to specific areas as shown in Figures 15, 16, and 17. Category D ducts seemed to follow no set pattern, but showed up randomly across the North Pacific Ocean as shown in Figure 18. These ducts did not appear with enough frequency to warrant enclosing them in a single large area.

In describing category A, B, and C duct variations for the heating period a counterclockwise rotation around the North Pacific Ocean is again utilized, beginning with sector 5. In sector 5 the single sub-thermocline ducts observed were predominantly in sub-category A-1, with the only exception being three sub-category B-1 ducts located very near the mouth of the Columbia River.

Moving north into sector 2, only category A ducts were observed, and these, with one exception, were all in sub-category A-1. These sub-category A-1 ducts were so prominent east of 165 W that, of a total of 123 ducts observed in combined sectors 2 and 5, 85.4 percent were in sub-category A-1. Even more striking is the fact that in these same two sectors, eliminating the category D ducts and considering only the 109 single sub-thermocline ducts observed, 96.4 percent were in sub-category A-1.

In sector 1 a combination of category A, B, and C ducts were observed. To the south of the Aleutian Island chain, but still in sector 1, only category A ducts were found, and these were all in sub-categories A-1 or A-3. Sub-thermocline ducts to the north of the Aleutian Island chain grew not only

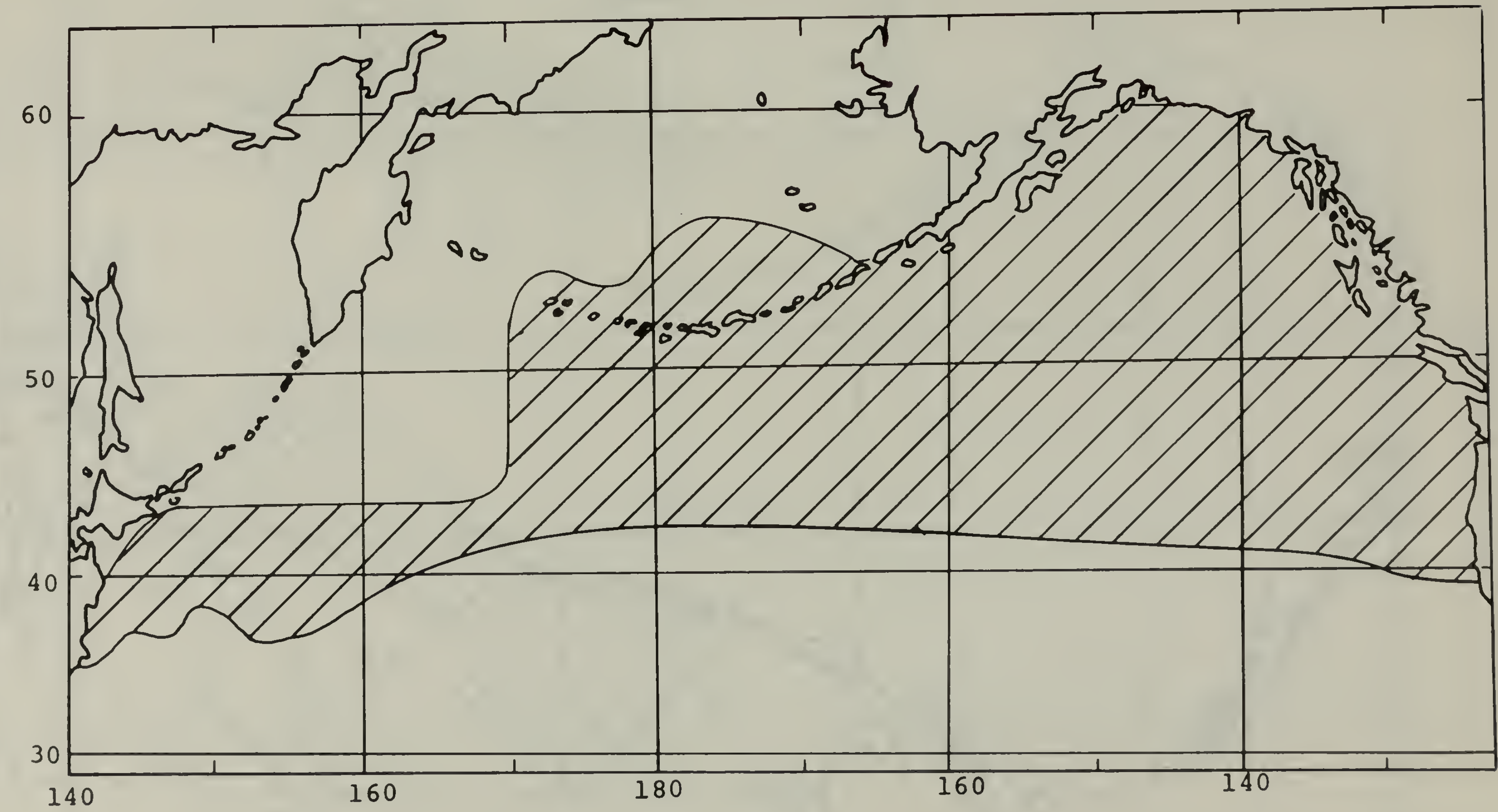

Figure 15

AREA OF NORTH PACIFIC IN WHICH CATEGORY A DUCTS WERE FOUND

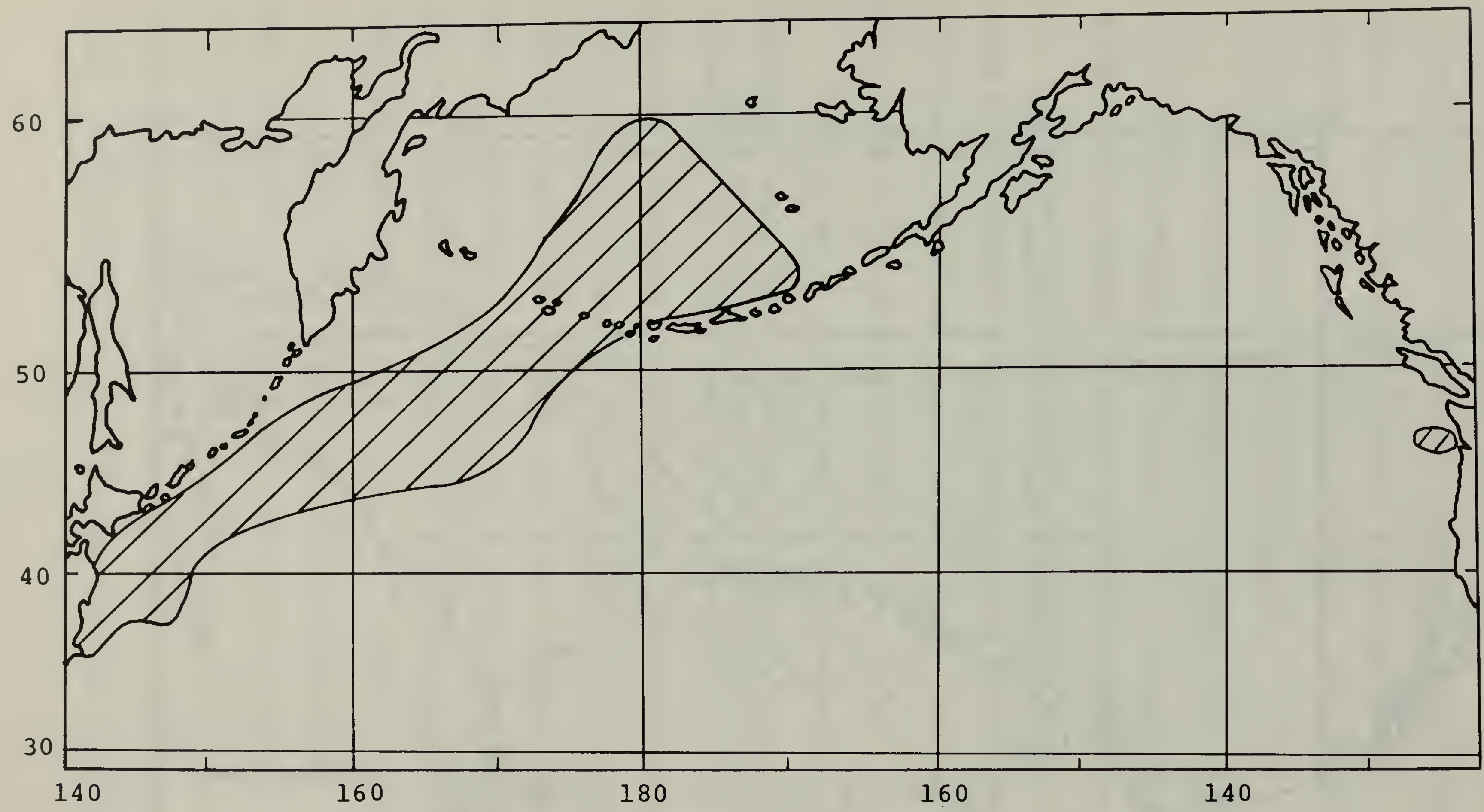

Figure 16

AREAS OF NORTH PACIFIC IN WHICH CATEGORY B DUCTS WERE FOUND

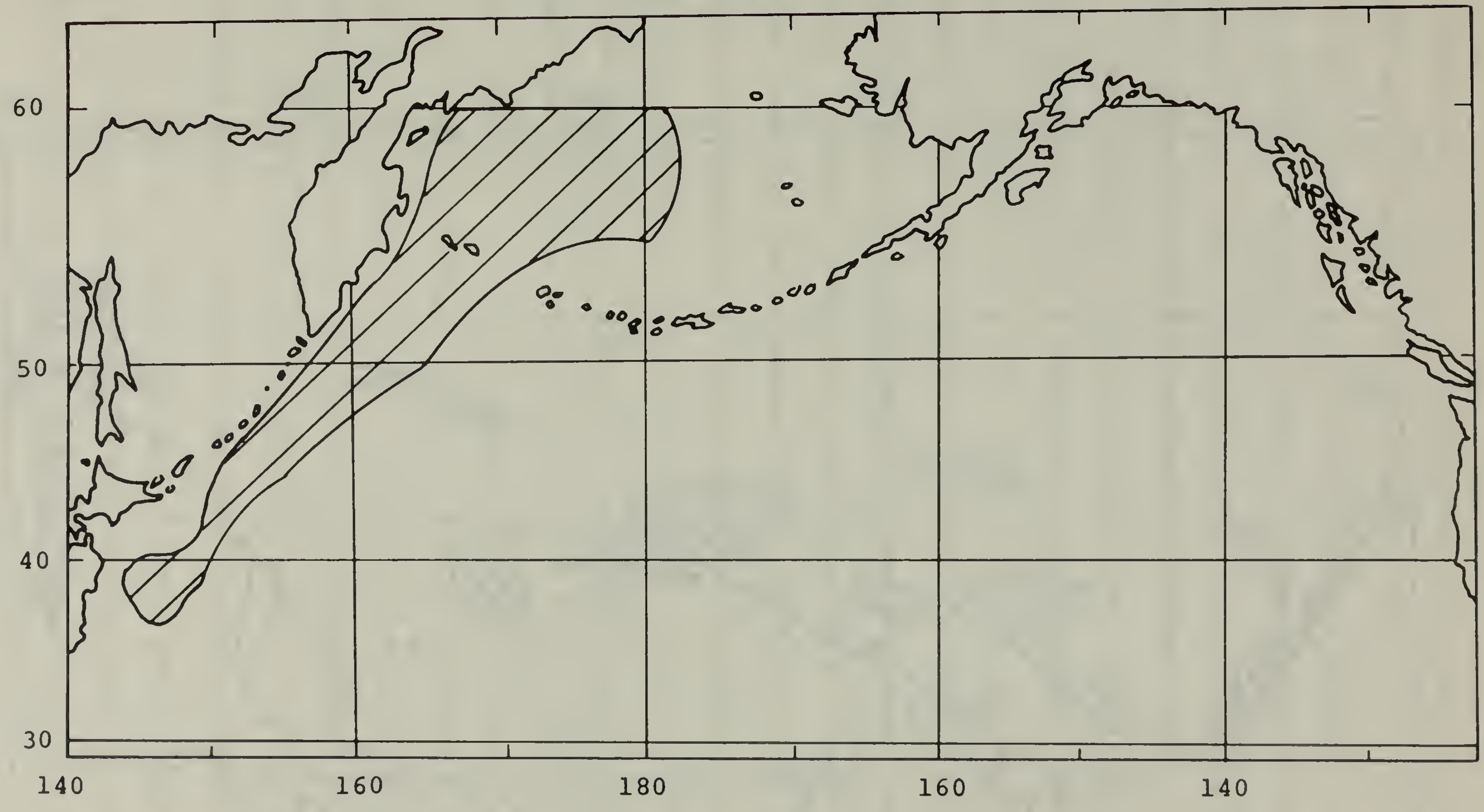

Figure 17

AREA OF NORTH PACIFIC IN WHICH CATEGORY C DUCTS WERE FOUND

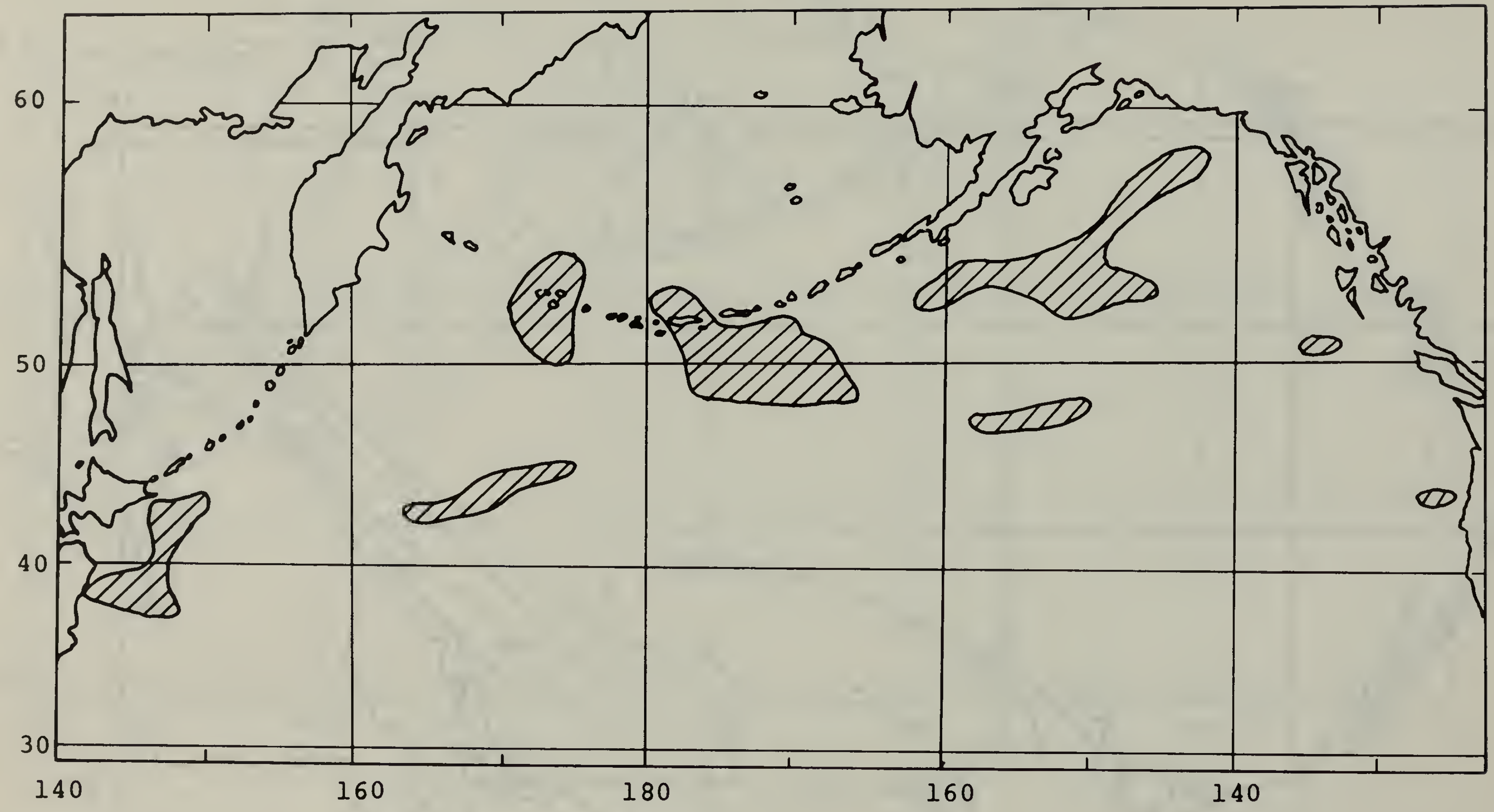

Figure 18

AREAS OF NORTH PACIFIC IN WHICH CATEGORY D DUCTS WERE FOUND

in magnitude, but also in thickness, and their depths of duct mean axes deepened. In this part of sector 1, sub-category A-3, A-5, B-3, B-5, C-3, and C-5 ducts were prevalent. It was in the northwest portion of sector 1 that category C ducts first appeared, and these ducts remained confined in sector 1 to that area north of 53 N and west of 178 W.

The category C ducts continued west into sector 3 to the east coast of the Kamchatka Peninsula, and then south along a southwesterly belt running almost parallel to the western boundary of sector 3. Along this belt, duct thicknesses grew, and sub-category C-5 and C-6 ducts became prominent. A dense grouping of sub-category B-6 ducts were clustered just off the Japanese islands of Honshu and Hokkaido, with sub-category A-4 ducts appearing frequently near the northern boundary of the Kuroshio. A probable contribution to the formation of these A-4 ducts was Kuroshio meanders. Where larger ducts may have existed, their upper portions were warmed by a Kuroshio meander, eliminating the top half or more of the ducts, but leaving deep category A remnants. The top of these A-4 ducts averaged 338 meters depth; however, the duct mean axes averaged approximately 415 meters. This seems to agree with the depth reached by the upper layer of the Kuroshio, which Hidaka (1966) sets at about 400 meters.

In sector 4 three category B ducts were observed in the far northwest corner. All other single ducts in this sector were in category A. Ducts east of 180 degrees longitude were

primarily in sub-category A-1; however, west of 180 degrees longitude a combination of A-1, A-4, A-5, and A-6 ducts were found, grouped randomly throughout this portion of the sector, with the exception of the far northwest corner which contained only the three category B ducts.

CHAPTER VI

CONCLUSIONS

Sub-thermocline ducts have been shown to exist in the North Pacific Ocean from year to year, and can be considered characteristic of the North Pacific north of 42 N. These ducts show a definite pattern of seasonal and positional variations which can be predicted from historical analysis with some degree of accuracy.

In the Subarctic North Pacific salinity in the characteristic halocline does not increase much more than one part per thousand, whereas temperature in that same halocline has been seen to increase up to three or four degrees Centigrade. Considering average salinity and temperature values for this region, a one part per thousand salinity increase holding temperature and depth constant will increase sound speed 1.4 meters per second. On the other hand a one degree Centigrade temperature change holding salinity and depth constant will increase sound speed 4.3 meters per second. With this major dependence of sound speed on the temperature profile, sub-thermocline duct knowledge can play a significant role in the study of sound in the sea.

CHAPTER VII

RECOMMENDATIONS

This work mainly sets up basic guidelines in a relatively untouched field of study of the ocean. The sub-thermocline duct should be studied in greater detail in the North Pacific Ocean in order to refine boundaries or limits on areas discussed in this thesis. Investigation into sub-thermocline duct activity in other regions of the world ocean should also be conducted.

Time did not permit the study of sub-thermocline duct effects on sound ray paths, and this should be accomplished considering various categories of ducts and various source and receiver depths in these ducts.

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13. ABSTRACT

This thesis describes a method by which near-surface temperature inversions in the ocean may be classified. Although categories of sub-thermocline ducts for sound transmission, formed as a result of these temperature inversions, have been studied in detail in the North Pacific Ocean, classifications are general enough to be applied to ducts in other regions.

A considerable variety of sub-thermocline ducting is present in the North Pacific. This variability shows both a seasonal and a positional dependence which may be explained on a stability basis utilizing data obtained from selected Nansen casts reported for stations throughout the North Pacific.

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